

ELECTROWEAK PHYSICS RESULTS AT CDF

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The Run II physics program of CDF is proceeding with approximately 200 pb^{-1} of analysis quality data collected at the center-of-mass energy of 1.96 TeV. The Electroweak measurements are among the first and most important benchmarks towards the best understanding of the detector and testing of the Standard Model. We present precision measurements of the W and Z inclusive cross sections and decay asymmetries, recent results in di-boson physics and their sensitivity to new physics, and preliminary studies for the W mass measurement.

1 Introduction

Studying the electroweak sector of the Standard Model (SM) is pivotal in the CDF physics programme for Run II at the Tevatron. The large number of W bosons and the possibility to explore high mass Z/γ^* are exceptional opportunities at hadron-colliders. and some measurements at the Tevatron have unique sensitivities to the ratio of the $u(\bar{u})$ to $d(\bar{d})$ parton distribution functions in the proton(anti-proton). The measurement of the W mass, one of the primary goals of the CDF electroweak programme, is central to constraining the mass of the SM Higgs boson and thus to a deep and complete understanding of the Standard Model and its extensions. W and Z boson cross section measurements are key milestones in the understanding and calibration of the detectors, and a starting point for any advanced measurement or discovery. Studies of boson asymmetries and di-boson production processes are based on clean and well-understood signatures which are robust tests of the Standard Model and allow one to explore beyond-the-Standard-Model scenarios with the total integrated luminosity of 4 to 8 fb^{-1} expected in this decade. Both the accelerator¹ and the CDF detector have undergone major upgrades in order to handle the increase in luminosity and energy achieved during Run II. The increase in center-of-mass energy from 1.8 to 1.96 TeV is directly mirrored in an increase of the production cross

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Table 1: The raw event yields and resulting inclusive W, Z cross sections measured by the CDF experiment.

Channel(mode)	η_{lepton} coverage	\mathcal{L}	Raw yield	Background	A $\cdot\epsilon$	$\sigma \cdot \text{Br}$
$W^\pm \rightarrow e^\pm \nu$	$ \eta < 1$	72	37574	4.4%	17.9%	$2782 \pm 14_{\text{stat}}^{+61} \pm 167_{\text{lum}} \pm 167_{\text{syst}}$ pb
$W^\pm \rightarrow e^\pm \nu$	$1.1 < \eta < 2.8$	64	10461	8.7%	5.2%	$2874 \pm 34_{\text{stat}} \pm 67_{\text{syst}} \pm 172_{\text{lum}}$ pb
$W^\pm \rightarrow \mu^\pm \nu$	$ \eta < 1$	72	37574	10.6%	14.4%	$2772 \pm 16_{\text{stat}}^{+64} \pm 166_{\text{lum}} \pm 160_{\text{syst}}$ pb
$W^\pm \rightarrow \tau^\pm \nu$	$ \eta < 1$	72	2345	26.0%	0.9%	$2620 \pm 70_{\text{stat}} \pm 210_{\text{syst}} \pm 160_{\text{lum}}$ pb
$Z^0 \rightarrow e^+ e^-$	$1^{\text{st}} e: \eta < 1; 2^{\text{nd}} e: \eta < 2.8$	72	4242	1.5%	22.7%	$255.2 \pm 3.9_{\text{stat}}^{+5.5} \pm 15.3_{\text{lum}} \pm 5.4_{\text{syst}}$ pb
$Z^0 \rightarrow \mu^+ \mu^-$	$ \eta < 1$	72	1785	0.7%	10.2%	$248.9 \pm 5.9_{\text{stat}}^{+7.0} \pm 14.9_{\text{lum}} \pm 6.2_{\text{syst}}$ pb

sections, which is approximately 10% for the W, Z and in the case of the top is about 30%^{2,3}. The upgraded CDF detector has a completely new tracking system, extended muon coverage and redesigned trigger and DAQ systems. The new drift chamber ($|\eta| < 1.0$) and three silicon detectors ($|\eta| < 1.8$) along with the new calorimeter in the end-cap region (“Plug”) cover the whole pseudo-rapidity range up to $|\eta| = 3.6$.

2 $W^\pm \rightarrow \ell^\pm \nu$ and $Z^0 \rightarrow \ell^+ \ell^-$ inclusive cross sections

The W and Z cross section measurements, with their high event yields and relatively clean signatures, not only provide a solid test of the Standard Model but are extensively used in the calibration of the calorimeter energy scales. Furthermore, a precision measurement of the ratio of the cross sections is sensitive to new physics states which might decay preferentially in either W or Z . In addition, confidence in these results allows them to be used as normalization for successive measurements (such as the luminosity measurement and the top production cross section), for which systematic and theoretical uncertainties would cancel in the ratio. Events are selected requiring one high- p_T isolated lepton and a second lepton (with slightly looser requirements) for the Z , or large missing transverse energy in the case of the W . The results presented here include the measurements relative to the region of pseudo-rapidity $|\eta| < 1$ and the new measurements of the W and Z cross sections performed using leptons reconstructed in the forward regions of the detector. These include a new W cross section measurement using electrons reconstructed in the Plug calorimeter, and a combined Z cross section, where the first electron is found in the central region ($|\eta| < 1.0$) and the second can be either in the central(CC) or in the Plug(CP) ($|\eta| < 2.8$). The measurements in the muon channel include the muons reconstructed in the Central Muon Extension (CMX) sub-detector which extends the coverage from $|\eta| < 0.6$ up to $|\eta| < 1$. One of the most interesting new results of Run II at CDF is the $W^\pm \rightarrow \tau^\pm \nu$ cross section measurement, which uses the dedicated trigger selecting events through the hadronic decay of the tau in association with large missing energy. Although all these measurements still use the first 72 pb⁻¹ of data, time has been spent to obtain a thorough understanding of the systematic effects involved, which already limited the measurements one year ago⁴. Thanks to this effort the systematic uncertainty has been reduced by one percentual point compared to the previous result. Distributions of the Z invariant mass and the W transverse mass in the electron and muon channels respectively are shown in Figure 1. The event yield for each channel, background fraction, acceptance times efficiency and measured cross-section are shown in Table 1; the increase in acceptance due to the extended coverage in pseudo-rapidity can be observed⁴. The combined measurements in the muon and electron channel^b are:

$$\begin{aligned}
 \sigma(p\bar{p} \rightarrow Z^0/\gamma^* \rightarrow \ell\ell) &= 254.3 \pm 3.3_{\text{stat}} \pm 4.3_{\text{syst}} \pm 15.3_{\text{lum}} \text{ pb} \\
 \sigma(p\bar{p} \rightarrow W^\pm \rightarrow \ell\nu) &= 2777 \pm 10_{\text{stat}} \pm 52_{\text{syst}} \pm 167_{\text{lum}} \text{ pb}.
 \end{aligned}$$

^bThe measurement of the $W^\pm \rightarrow e^\pm \nu$ cross section using the electrons reconstructed in the Plug calorimeter has not been included in the combination.

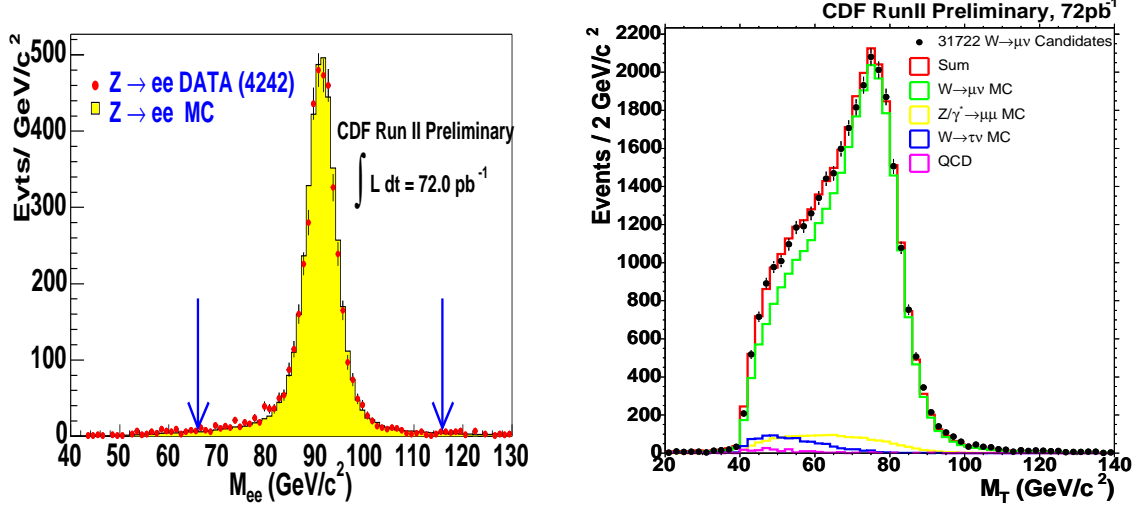


Figure 1: *On the left:* $Z^0 \rightarrow e^+e^-$ invariant mass distribution from CC and CP events; the arrows indicate the invariant mass window in which the measurement has been performed. *On the right:* $W^\pm \rightarrow \mu^\pm\nu$ transverse mass distribution from data(dots), Monte Carlo signal and all considered sources of background(histograms).

These measurements are in excellent agreement with the NNLO theoretical calculations at 1.96 TeV⁵ of $\sigma(p\bar{p} \rightarrow Z^0 \rightarrow \ell\ell) = 252 \pm 5$ pb and $\sigma(p\bar{p} \rightarrow W^\pm \rightarrow \ell\nu) = 2690 \pm 50$ pb, and previous measurements in literature⁶, as shown in Figure 2(left). CDF and DØ results are compared elsewhere in these proceedings⁷. From the $W^\pm \rightarrow \tau^\pm\nu$ and $W^\pm \rightarrow e^\pm\nu$ cross-section measurements CDF has extracted the ratio of the coupling constants $g_\tau^W/g_e^W = 0.99 \pm 0.02_{stat} \pm 0.04_{syst}$, probing lepton universality. The signal $Z^0 \rightarrow \tau_{lep}\tau_{had}$ has been observed; the major challenge to the upcoming measurement of the cross section is the study of the background, largely dominated by QCD di-jet events. Once finalized, this channel will be the ideal starting point for all analyses including taus, particularly searches for Supersymmetry in models with high values of $\tan\beta$, for which the branching ratio $A/h \rightarrow \tau\tau$ is enhanced⁸. From the ratio of the cross sections $\sigma(p\bar{p} \rightarrow W^\pm \rightarrow \ell\nu)$ to $\sigma(p\bar{p} \rightarrow Z^0 \rightarrow \ell\ell)$ CDF has extracted the value of the total decay width of the W boson, which has been found to be: $\Gamma(W \rightarrow \ell\nu) = 2071 \pm 40$ MeV, where the value is the combined value in the electron and muon channels and the uncertainty includes the statistical and systematic contributions. This value is consistent with the LEP direct measurement of 2.150 ± 0.091 GeV, the Run I CDF and DØ combined measurement of 2.115 ± 0.105 GeV, and the DØ Run II measurement of 2187 ± 128 MeV, obtained with 42 pb^{-1} of data in the electron channel⁷. This value alone is already as precise as the current world average value of 2092 ± 40 MeV, and it is the most precise experimental measurement of $\Gamma(W)$ up to now. In Figure 2(right) the CDF single and combined values are compared to the Standard Model expectation, other indirect measurements and the DØ Run II measurement. From the ratios measured separately in the electron and muon channels, CDF has also extracted the ratio of the coupling constants $g_\mu/g_e = 1.011 \pm 0.018_{stat+syst}$, another probe of lepton universality.

3 Z^0 forward-backward asymmetry

A forward-backward asymmetry can be observed in the decay of the leptons in the process $\bar{q}q \rightarrow Z/\gamma^* \rightarrow \ell\ell$, due to the presence of both vector and axial-vector couplings of electroweak bosons to fermions. The measurement of A_{fb} , defined as $A_{fb} = \frac{N_F - N_B}{N_F + N_B}$, where N_F and N_B are the number of forward and backward events (in the rest frame of the lepton pair) respectively, is a direct probe of the strengths of the couplings involved. Furthermore, a measurement of A_{fb} is

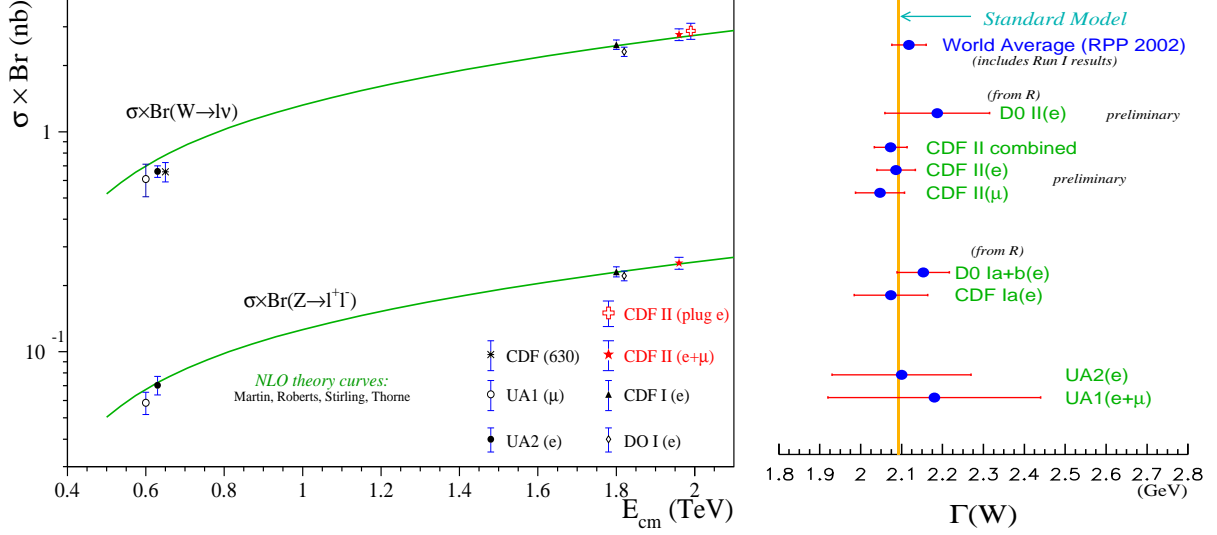


Figure 2: *On the left:* Recent $Z^0 \rightarrow \ell^+\ell^-$ and $W^\pm \rightarrow \ell^\pm\nu$ cross section measurements as a function of the center of mass energy for the CDF experiment, compared to other measurements in literature and to the NNLO calculation (as described in the text). *On the right:* Value of the total decay width of the W boson extracted from the measurement of the ratio of the $W^\pm \rightarrow \ell^\pm\nu$ to $Z^0 \rightarrow \ell^+\ell^-$ cross sections for the CDF and DØ experiments, compared to the Standard Model expectation (yellow band) and other indirect measurements in literature.

sensitive to the presence of high mass Drell-Yan(DY) resonances outside the Standard Model⁹. The CDF measurement of A_{fb} in 72.0 pb^{-1} (shown in Figure 3) is one of the first analyses in Run II to make use of the full coverage $|\eta| < 3.0$ provided by the new Plug calorimeter. The selection of the events requires a high- p_T electron in the central region and a second one anywhere in the detector, with the main background consisting of di-jet QCD events. While the LEP measurement¹⁰ is better in the low invariant mass region, the measurement for $M_{ee} > 200 \text{ GeV}$ is unique at the Tevatron. This measurement is currently being updated with the full 200 pb^{-1} of data.

4 Di-boson results

Associated $W\gamma$ and $Z\gamma$ production is an important test of the non-Abelian nature of the SM as it is sensitive to triple-gauge boson interactions and thus to physics beyond the Standard Model. Using the same selection as in the W and Z inclusive cross section measurements but with the addition of a high-energy ($E_T^\gamma > 7 \text{ GeV}$) photon isolated from the lepton ($\Delta R(\gamma-\ell) > 0.7$), CDF measured the cross sections $\sigma(p\bar{p} \rightarrow W\gamma) \cdot \text{Br}(W \rightarrow \ell\nu)$ and $\sigma(p\bar{p} \rightarrow Z\gamma) \cdot \text{Br}(Z \rightarrow \ell\ell)$ in 202 pb^{-1} of Run II data. The values along with the number of events expected and observed in the data are shown in Table 2. All the measurements are consistent with the SM predictions^{11,12}

Table 2: The raw event yields and resulting $W, Z\gamma$ cross sections measured by CDF in 202 pb^{-1} of data.

Channel(mode)	N events expected (signal MC + SM background)	N events observed in the data	$\sigma \cdot \text{Br}$
$W^\pm\gamma \rightarrow \ell^\pm\nu\gamma$	$255.63 \pm 2.13_{\text{stat}} \pm 26.43_{\text{syst}}$	259	$19.7 \pm 1.7_{\text{stat}} \pm 2.0_{\text{syst}} \pm 1.2_{\text{lum}} \text{ pb}$
$Z^0\gamma \rightarrow \ell^+\ell^-\gamma$	$70.46 \pm 4.00_{\text{syst}}^{(*)}$	69	$5.3 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}} \pm 0.3_{\text{lum}} \text{ pb}$

(*) The statistical uncertainty from the MC samples is negligible.

of $\sigma(p\bar{p} \rightarrow W\gamma) \cdot \text{Br}(W \rightarrow \ell\nu) = 19.3 \pm 1.3 \text{ pb}$ and $\sigma(p\bar{p} \rightarrow Z\gamma) \cdot \text{Br}(Z \rightarrow \ell\ell) = 5.4 \pm 0.4 \text{ pb}$. Figure 4(left) shows the transverse mass distribution reconstructed using the lepton, photon and missing energy information, and the transverse energy of the photon in $W\gamma$ events (right). As the presence of Anomalous Gauge Couplings (AGC) in the three bosons vertex would modify the

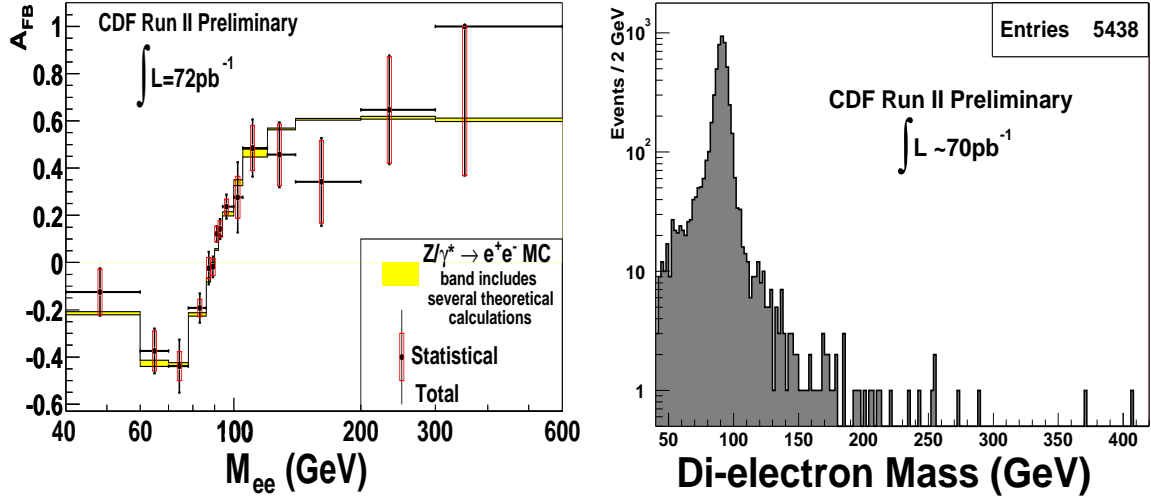


Figure 3: *On the left:* CDF measurement of the forward-backward asymmetry in the di-electron channel for the entire electron-positron invariant mass spectrum, compared to the theory predictions. *On the right:* Invariant mass spectrum of the Z candidate events used in the measurement of A_{fb} .

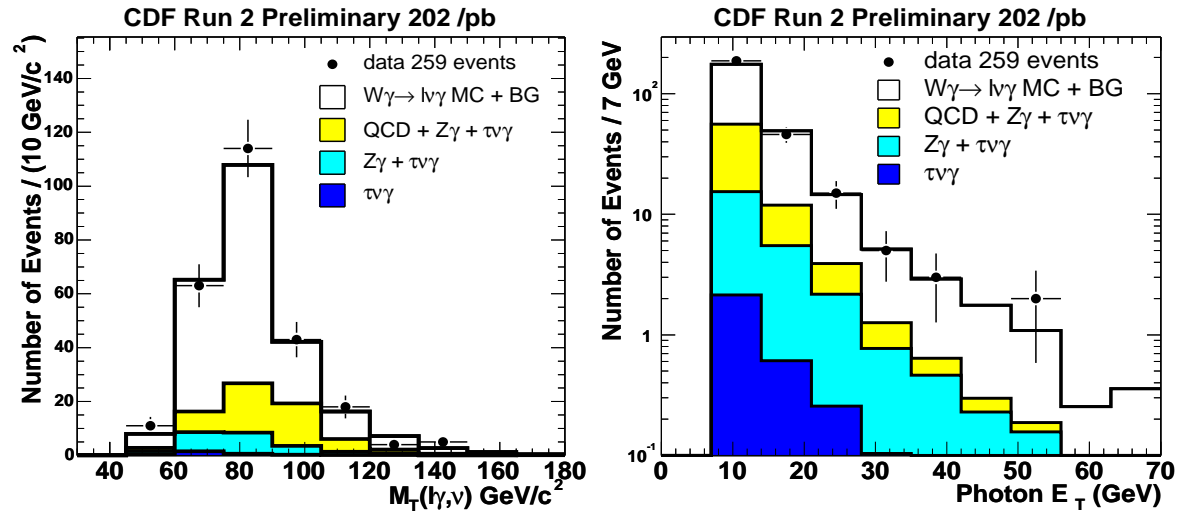


Figure 4: *On the left:* Transverse mass distribution of the lepton, photon and neutrino for $W\gamma$ events. *On the right:* Photon E_T distribution of $W\gamma$ events on a logarithmic scale for the MC signal (open histogram), data (dots) and all the expected sources of background. Presence of anomalous coupling would modify the photon spectrum towards higher values of E_T .

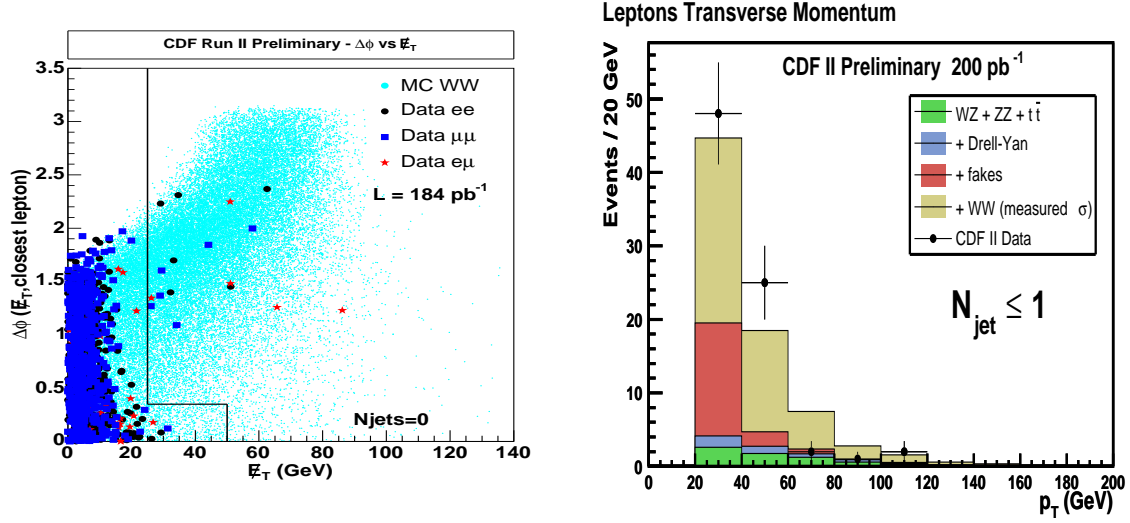


Figure 5: $\Delta\phi(\ell_T, \ell)$ as a function of ℓ_T for the 17 WW candidate events from the “di-lepton” analysis (left), and the p_T distribution of the two lepton tracks of the 39 “lepton+track” WW events (right). In the latter all the sources of expected background are also indicated.

latter distribution boosting the photon towards higher E_T ¹³, the photon spectrum is a direct test of the presence of AGC. Preliminary results on Anomalous Gauge Coupling extraction from the photon E_T spectrum are expected by the end of 2004.

Heavy di-boson measurements such as WW , WZ and ZZ also lead to new limits on triple gauge boson couplings and are important background to $t\bar{t} \rightarrow \ell\ell + \text{jets}$, Higgs and exotic signatures. CDF has looked for WW events in two separate complementary ways. One analysis has been optimised for signal over background ratio, selecting events with two isolated leptons (according to similar criteria as the ones used in the inclusive cross section analyses), large missing energy and the absence of jets. The second analysis applies looser selection criteria on the second lepton (which can also be just a high- p_T track, allowing the presence of electrons, muons and taus), with the aim of improving the acceptance of the signal. The number of observed and expected events are shown in Table 3, along with the cross section results for the first (“di-lepton”) and second (“lepton+track”) method. The results are consistent with each other and with the theoretical calculation of 12.5 ± 0.8 pb¹⁴. Figure 5 shows the kinematic distribution of the “di-lepton”

Table 3: The raw event yields and resulting WW cross sections measured by the “di-lepton” and “lepton+track” analyses in CDF with 202 pb⁻¹ of data.

Method	N events expected (signal MC + SM background)	N events observed in the data	S/B	$\sigma(p\bar{p} \rightarrow WW)$
di-lepton	$16.1 \pm 1.6_{\text{stat+syst}}$	17	2.3	$14.3^{+5.6}_{-4.9 \text{ stat}} \pm 1.6_{\text{syst}} \pm 0.9_{\text{lum}}$ pb
lepton+track	$31.5 \pm 1.0_{\text{stat}}$	39	1.1	$19.4 \pm 5.1_{\text{stat}} \pm 3.5_{\text{syst}} \pm 1.2_{\text{lum}}$ pb

events compared with the Monte Carlo prediction (left), and the p_T distribution of the leptons in the “lepton+track” sample (right).

5 Towards the W mass

The mass of the W boson is one of the most important parameters of the Standard Model, as its precise knowledge, combined with that of the top mass, results in a significant constraint on the mass of the as yet unobserved Higgs particle. From the experimental point of view this is a challenging measurement as it requires a precise knowledge of the detector and the best

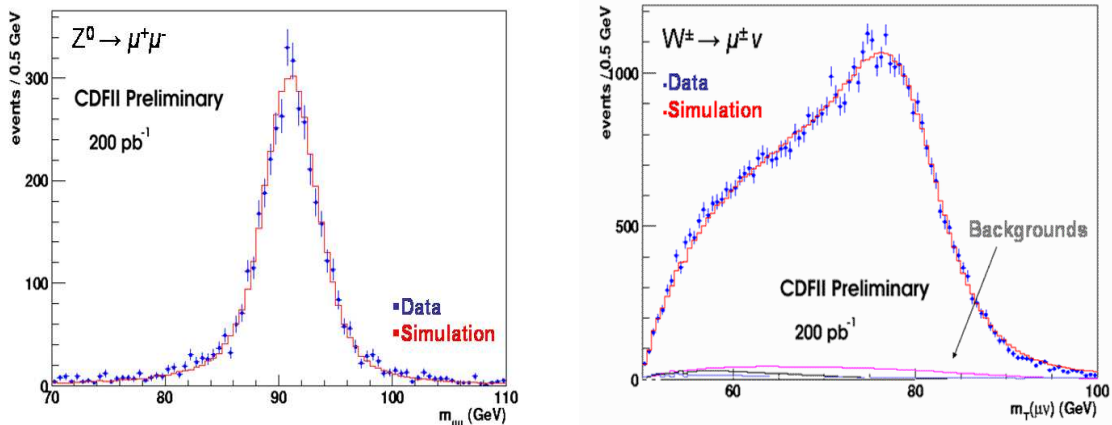


Figure 6: On the left: $Z^0 \rightarrow \mu^+\mu^-$ invariant mass distribution from data (dots) and simulation (histogram). On the right: $W^\pm \rightarrow \mu^\pm\nu$ transverse mass distribution from data (dots) and simulation (histogram). In the latter the contributions from all sources of background are also shown.

understanding of its performance. The method adopted by CDF consists in using Monte Carlo templates with different values of the W mass to fit several distributions of signal plus total expected background, and extract the value of M_W from the distribution which best matches the data. Work is already in progress at CDF in understanding the key components relevant to this measurement: the track momentum scale and the missing energy resolution. Figure 6(left) compares the $Z^0 \rightarrow \mu^+\mu^-$ invariant mass distribution in data and Monte Carlo signal, generated with RESBOS¹⁵ and simulated using the best knowledge of the detector. This distribution will be used to test the linearity of the momentum scale, which will be measured using J/Ψ events. The W transverse mass distribution, also shown in Figure 6(right), is directly affected by the resolution of the missing energy measurement, representing the energy of the escaping neutrino. CDF and DØ have recently published¹⁶ the Run I combined result of $M(W) = 80.456 \pm 0.059$ GeV, with a statistical uncertainty of approximately 40 MeV. The goal of the Run II analysis is to use data to control the systematic uncertainties, such that they scale with the statistics of the data. From the tail of the W transverse mass distribution a direct measurement of $\Gamma(W)$ can be performed. As most of the systematics effects important in the extraction of the width are the same studied for the W mass measurement, a preliminary result of the direct measurement of $\Gamma(W)$ will naturally follow the W mass measurement expected by the summer 2004.

6 Conclusions and prospects

Run II at the Tevatron is well under way. The CDF detector is fully commissioned and is taking high-quality physics data. The Electroweak physics programme has reestablished the basic measurements, benchmarks for the understanding of the detector backgrounds and lepton identification, and the precision measurements are already competitive with the Run I results. We expect to finalize results on di-boson production processes and differential cross sections for summer 2004, along with a preliminary measurement on the W charge asymmetry and W mass.

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